Improving Space Surveillance with Space-Based Visible Sensor

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Abstract

The Midcourse Space Experiment satellite was launched in 1996. A principal sensor on board the satellite is the Space-Based Visible (SBV) sensor, a visible-band electro-optical camera designed at Lincoln Laboratory. The program has just completed three years of Contributing Sensor operations under the Advanced Concept Technology Demonstration (ACTD) program. The SBV has transitioned to an operational sensor under Space Command sponsorship. This paper describes recent modifications, made under the ACTD program, to both spacecraft and ground systems that have increased the productivity of the sensor from 200 deep space tracks/day to over 350 tracks/day. The onboard SBV software has been modified to utilize the redundant signal processor to process information in parallel. A new mode of operations has also been implemented that exploits the geometry of geosynchronous orbits to provide a very efficient coverage of the geosynchronous belt. Details of these modifications and initial results will be provided.

Operational Impact of Space-Based Space Surveillance

After completing a successful demonstration of space-based space surveillance, the SBV sensor began contributing sensor operations in April 1998. The SBV Processing and Operations Control Center (SPOCC) receives daily tasking from Space Command. The spacecraft is operated 8 hours per day, 7 days per week performing space surveillance. The description of the operations and data processing was provided in previous papers [2,3]. Sensor characteristics relevant to routine space surveillance are summarized in Table 1. There are two unique properties of the SBV sensor that are being exploited for space surveillance [4,5]. First, the SBV sensor is on an orbiting platform and has access to the entire geosynchronous belt. Second, the wide field of view of the sensor allows for efficient search operations and for multiple resident space objects (RSOs) to be detected simultaneously. Surveillance data is collected in a sidereal track mode, where the stars appear as point sources and the RSOs appear as streaks. Routine surveillance data is then processed through the onboard signal processor to extract the star and streak information as illustrated in Figure 1.

TABLE 1

SBV SENSOR CHARACTERISTICS

Spectral Range	0.3 - 0.9 μm
Spatial Resolution	12.1 arcsec/pixel
Field of View per CCD	1.4 x 1.4 Deg
Aperture, f/no	15 cm, f/3
Number of Frames per Frameset	4 – 16 frames
Frame Integration Times	0.4, 0.625, 1, 1.6 sec
Frame Sizes	420x420 pixels

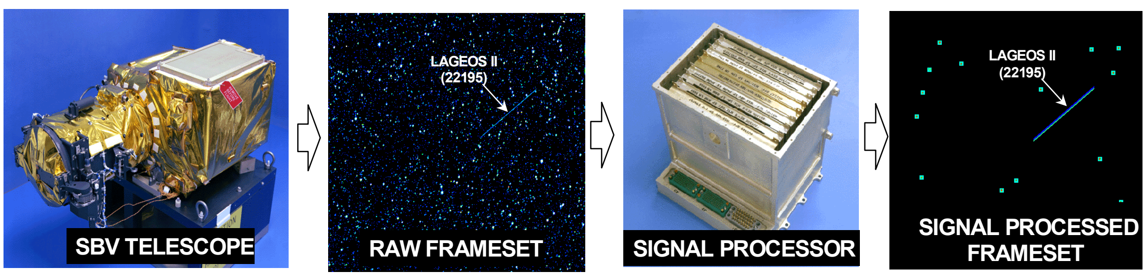


Figure 1. The SBV sensor consists of a high stray-light rejection telescopes, which contains four 420x420-pixel charge-coupled-device (CCD) that generate a raw frameset. The onboard signal processor processes the focal-plane images to yield star and streak reports, which is used to construct the signal, processed frameset image. The signal processed data are used for routine space surveillance of resident space objects (RSOs).

SBV is demonstrating the unique capabilities of a space-based space surveillance sensor. The unique nature of this sensor has not precluded improvements from being made to the system. Modifications to both ground and spacecraft systems have been made. Improvements undertaken early in the ACTD focused on increasing the efficiency of scheduling observations by collecting data on multiple RSO simultaneously and by reducing the maneuver time required by the MSX spacecraft. These efforts are described in detail in previous papers [1,2].

Improving the Capability of SBV

During the second half of ACTD operations, additional improvements were made to both ground and spacecraft systems to enhance the capabilities of the SBV sensor. Space surveillance with SBV involves scheduling of RSO observations, uplinking of SBV

commands, data collection and signal processing with the telescope and signal processor, maneuvering by the MSX spacecraft, and finally downloading and data reduction of SBV observations. Due to funding and spacecraft access limitations, SBV data collection is limited to a maximum of eight hours per day. Operational improvements to increase the productivity of SBV are thus limited to increases in the efficiency of scheduling RSO observations, and to increasing the efficiency of data processing onboard the spacecraft.

The remaining sections will discuss subsequent operational improvements that have been implemented during the second half of the ACTD period. The first of these improvements focus on increasing the efficiency of data processing onboard the spacecraft by exploiting redundant processing capability onboard the spacecraft. The second improvement further increases the effectiveness of scheduling observations by concentrating data collection on dense regions of the GEO belt and by performing these observations with a minimum number of maneuvers. These modifications represent a new mode of operations with emphasis on search operations versus tasked operations.

Dual Signal Processor Operations

The SBV sensor was designed with redundant components to allow for reliable operations in space [6,7,8]. The primary components of the SBV hardware consist of the camera, CCD sensor, analog electronics, experiment controller (EC), and the signal processor (SP). The experiment controller coordinates the operation of the CCD sensor and signal processor. The focal plane is configured such that a single failure will only impact two out of the four CCDs. Both the EC and SP have fully redundant channels. This redundancy has been exploited in two ways in the SBV program. First the redundant components were utilized in performing final testing of software upgrades to the on board systems. After thorough ground testing, software modifications for the SBV hardware were uploaded and first tested on the redundant component before being implemented in routine operations. This approach permitted upgrades to the SBV system with minimal impact on operations. The redundancy of SBV system was also utilized to increase the processing capability of the hardware. This section describes how the redundant signal processor was used to increase the capability to process data on board the spacecraft.

In nominal operations with only one signal processor, the CCD sensor is used to collect 8 frames of data with an integration time of 1.6 second per frame. Once the data is collected it is sent to the signal processor where star and satellite detections are extracted and stored as reports. The reports are initially stored within the memory of the SP and are moved to the EC before being downloaded to the ground. Data can be downloaded directly from the SP, but in the process of downloading it, it is deleted from the SP. Once the data is moved to EC, it can be downloaded multiple times. The timeline of processing data with a single SP is shown in Figure 2.

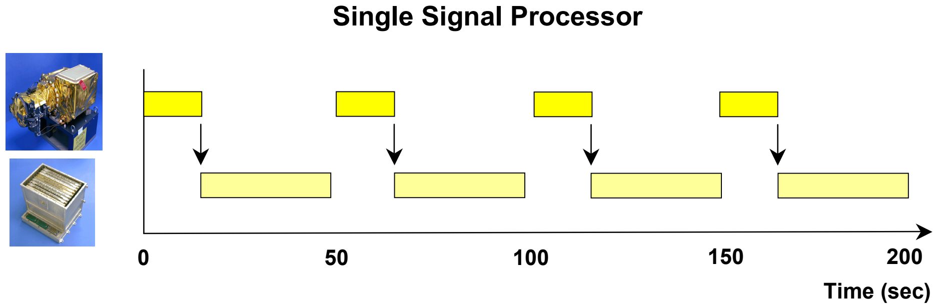


Figure 2. With only one signal processor in use the data must be processed through the signal processor before next frameset can be collected. The spacecraft can begin maneuvering while the last frameset is being processed.

Figure 2 shows that it takes approximately 200 sec to collect and process four successive framesets of data. The SBV hardware was designed and built with a redundant signal processor for reliability. The hardware is capable of operating both signal processors. Figure 3 shows how the second signal processor is utilized.

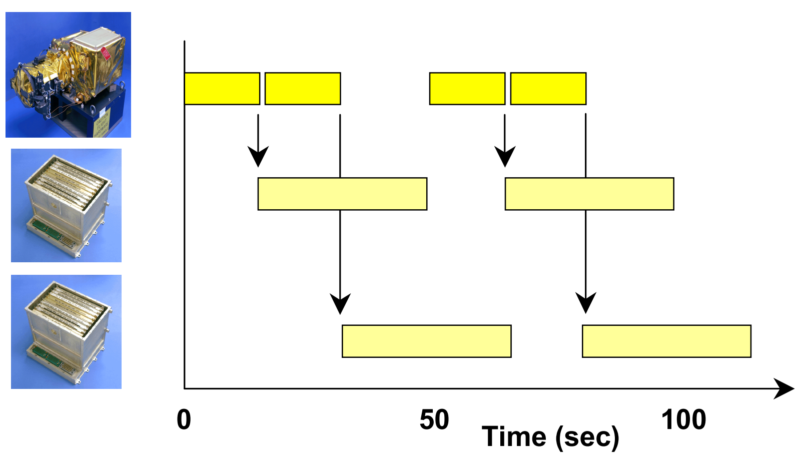


Figure 3. With two signal processors in use a second frameset can be immediately collected and sent to the second signal processor. As with the single processor case, the spacecraft can begin maneuvering while the last frameset is being processed.

Once one frameset is collected by the CCD sensor and sent to the signal processor, the second signal processor is immediately configured to receive the second frameset from the CCD sensor. The third frame is taken when the first signal processor is ready to receive the data. Finally the second signal processor is ready to receive the fourth frame-set. The spacecraft can begin maneuvering after the fourth frameset is taken, while the signal processor is processing this data. In dual signal processor mode it takes approximately 80 seconds to take four framesets of data, where it takes approximately 160 seconds to take the same amount of data using a single signal processor. In search

operations all four CCDs are used sequentially, and dual signal processor search operations can cover twice as much area than single signal processor search operations.

The Dual Signal Processor Operations was implemented by modifying onboard spacecraft software to toggle the two signal processors to receive the data from the CCD sensors. Once the memory in the signal processor is filled up, the data is moved to the experiment controller after which it can be downloaded. The onboard data flow was handled by a set of macros that were loaded onboard the spacecraft to redirect the data alternatively to both signal processors. A macro is a set of commands that is stored onboard the spacecraft that is addressable by a single command from the ground.

Geosynchronous Pinch Point Operations

The increased efficiency of dual signal processing operations made it possible to set up a search fence for geosynchronous objects that exploits the geometry of geosynchronous orbits. An interesting pattern of these orbits has developed over the last 40 years, resulting from specific launch and orbit maintenance strategy used by satellite operators. The pattern is driven by the operator's desire to exploit the natural effects of the sun, the moon, and the oblateness, or equatorial bulging, of the Earth, to maximize the satellite's lifetime and to minimize its operational (fuel) costs. It is through a combination of these natural effects and this behavior that creates a clustering of the ascending nodes that we refer to as "geosynchronous pinch points"[9]. It is through the exploitation of these pinch points that the SBV is able to significantly increase its productivity in search.

These pinch points become clearly visible, if the population of the geosynchronous belt is viewed over a 24-hour period, as shown in Figure 4. In this figure, each satellite progresses from left to right along a sinusoidal trajectory. The contours indicate the number of distinct satellites passing through a 1.4° x 1.4° region of inertial space over a 24-hour period, which is the field-of-view of one charge-couple device (CCD) on the SBV. The highest density regions, or pinch points, are centered at 0° declination and approximately 65° and 245° in right ascension. The dataset used for Figure 4 contains all the geosynchronous satellites.

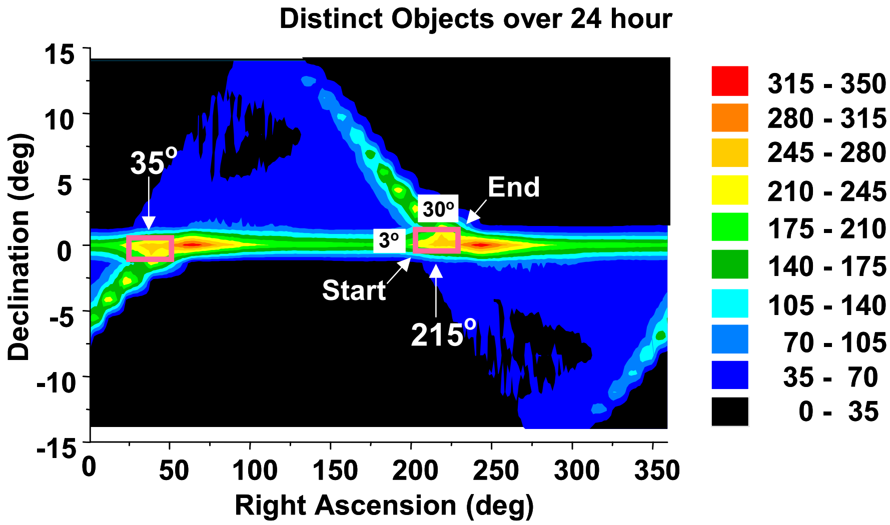


Figure 4. Satellite concentration in the geosynchronous belt over a 24-hour period. The population of geosynchronous satellites is viewed with respect to the inertial coordinates of right ascension and declination over the course of one day. These pinch points are locations on the geosynchronous belt which represent high concentrations of satellites at certain times of the day.

Pinch Point Implementation

Pinch point operations require the pinch point search region to be continuously observed over the 24 hours it takes geosynchronous objects to complete a single orbit. In practice SBV operations are limited to 8 hours per day, and the coverage of the search region has to be accomplished by searching the region in small time increments over 24 hours. By searching a region repeatedly with a constant revisit interval, it is possible to create a search region that covers the entire geosynchronous belt. Since the SBV is orbiting the earth, a constant revisit interval implies that pinch point region is searched once an orbit. The size of the search region resulted from a trade off between the time required to search the region and the amount of time the region is continuously visible. The resulting search pattern is shown in Figure 5.

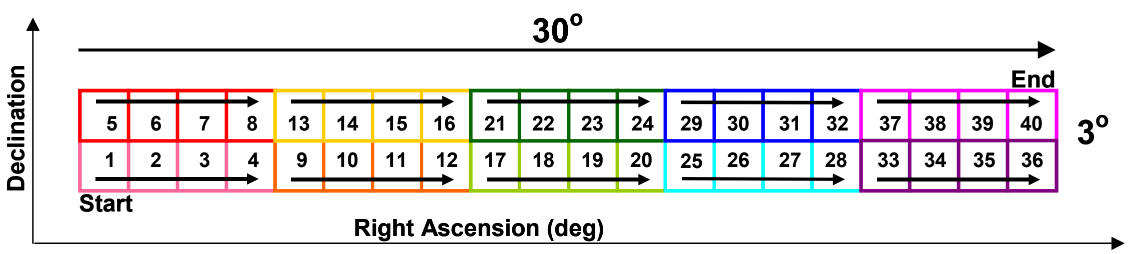


Figure 5. The search region is covered by generating a pattern with the four CCD array. The complete pattern consists of 40 framesets, which grouped into ten - four frameset blocks. The MSX spacecraft is only maneuvered between each of the four-frameset block. The resulting coverage is 30 degrees in right ascension and 3 degrees in declination.

This figure shows a box that is 30 degrees wide in right ascension and 3 degrees in declination, and consists of 10 groups of framesets. Each group consists of a frameset from each of the four CCDs. The spacecraft is only maneuvered between each group of framesets. The search region is covered by an array of 40 framesets, and is covered from left to right. Since GEO objects move from right to left, objects that are leaving the search region are observed first, and objects that are just entering the region at the end of the search interval are observed last. This search strategy also results in a slight overlap between framesets in longitude, and the 30-degree wide region in right ascension translates to a 25-degree wide region in longitude. With dual signal processor operation it takes approximately 30 minutes to cover the pattern shown in Figure 5. This search region is covered every orbit revolution as illustrated in Figure 6.

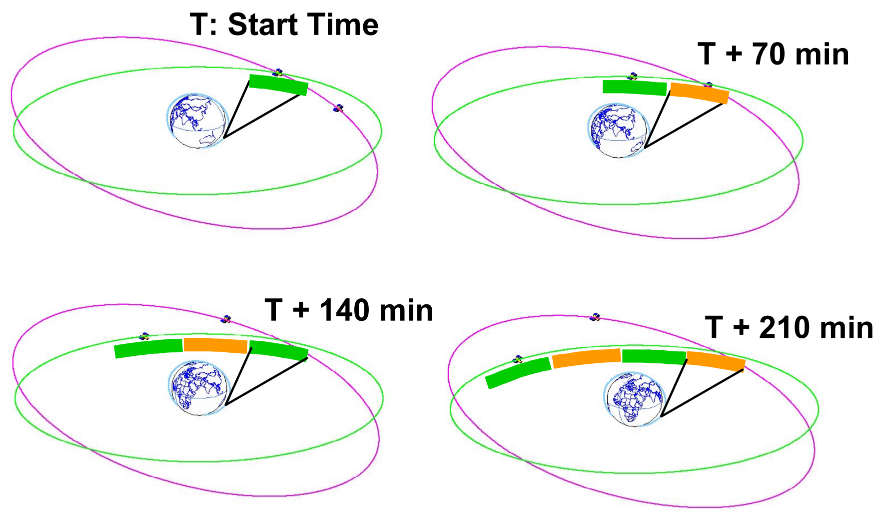


Figure 6. Four successive revisits of the pinch point illustrate the ability of pinch point operation to detect objects with 0 degree inclination (green orbit) and with 15 degree inclination (magenta orbit). The proper timing of twelve data collection at the pinch point allows up to 310 degrees of the GEO belt to covered

In practice, due to spacecraft operation constraints the pinch point is revisited twelve times per day resulting in coverage of approximate 300 degrees of the geosynchronous belt. The twelve pinch point revisits require approximately six hours spacecraft operations, which leave approximately two hours for tasked operations. An example timeline is shown in Figure 7, and it shows the distribution of pinch point revisits and the placement of two blocks of time devoted to tasked operations. The resulting operation timeline results in six hours of search operations and two hours of tasked operations.

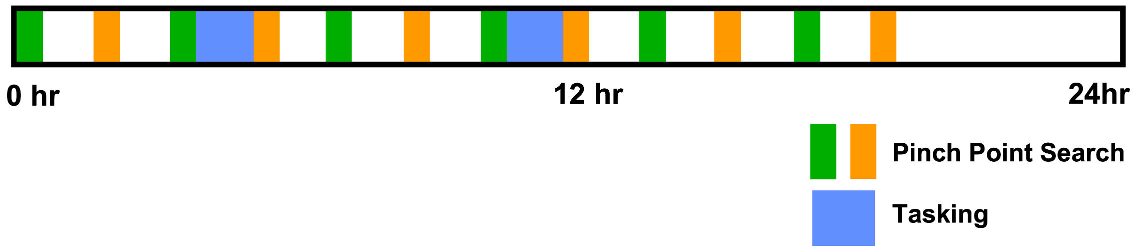


Figure 7. The twelve data pinch point collection periods are distributed over 19.4 hours. Two 70-minute blocks of time between revisits of the pinch point is devoted to tasking operations each day. These blocks are used for data collection of high priority objects and calibration objects.

The scheduling of pinch point data collection is also limited by several additional constraints that must be accounted for. These constraints are shown in Figure 8.

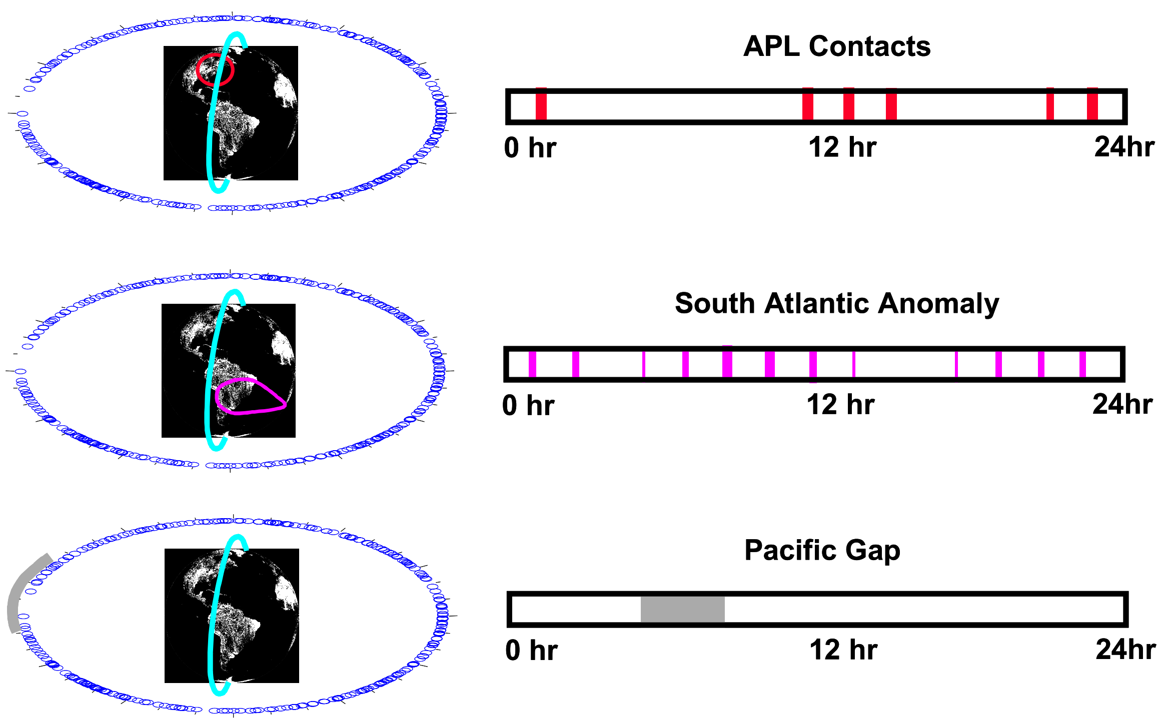


Figure 8. Times for the pinch point data collection are chosen to avoid conflicts with APL contacts with the MSX spacecraft, since these contacts are primary means to upload commands to the spacecraft and download the collected data. To maximize productivity, data collection is avoided when the spacecraft is in the South Atlantic Anomaly (SAA) and when the Pacific gap is passing through the pinch point.

There are three primary constraints that must be accommodated. The first constraint that must be accommodated is contacts with John Hopkins Applied Physics Laboratory (APL). These are times used by APL to upload commands and download data, and are times when the MSX spacecraft is passing above APL. The second constraint is times

that the MSX passes through the South Atlantic Anomaly (SAA). The SAA is a region of high density of high-energy electrons and protons. The high density protons interact with focal plane and prevent the detection of RSOs [1]. Finally, as the pinch point region is searched they are times when lower satellite density regions are observed. The lower satellite density region is a part of geosynchronous belt that is located over Pacific Ocean. It is desirable to position this 50-degree gap in pinch point coverage over this Pacific region.

These three constraints are combined with visibility of the pinch point region from MSX orbit and the timing of the pinch point data collection is adjusted by up to ten minutes to avoid conflicts. An example of a complete schedule is shown in Figure 9.

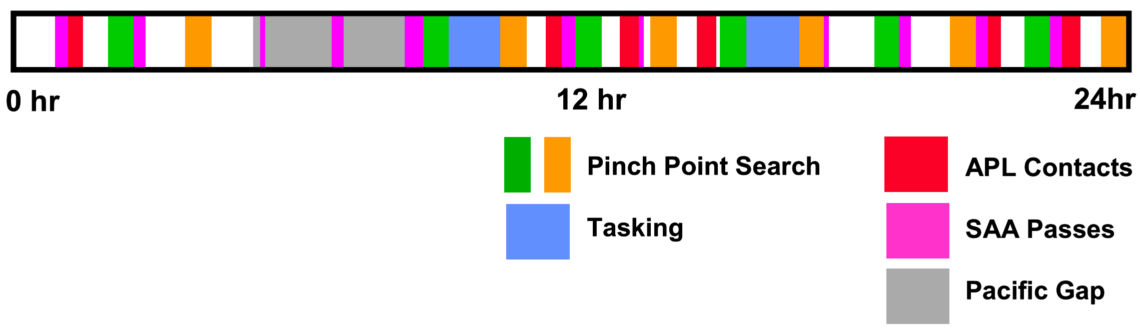


Figure 9. Schedule of twelve pinch point data collection periods subject to operational constraints. It is possible to schedule the data collection to avoid APL contacts and minimize data collection in the SAA and of the Pacific gap.

Impact of Operational Improvements

The impact of the modifications of both the ground and spacecraft systems has produced significant increases in the productivity of SBV. Figure 10 shows the average number of daily deep space tracks collected by SBV. In October 1997 SBV was producing approximately 50 deep space tracks per day.

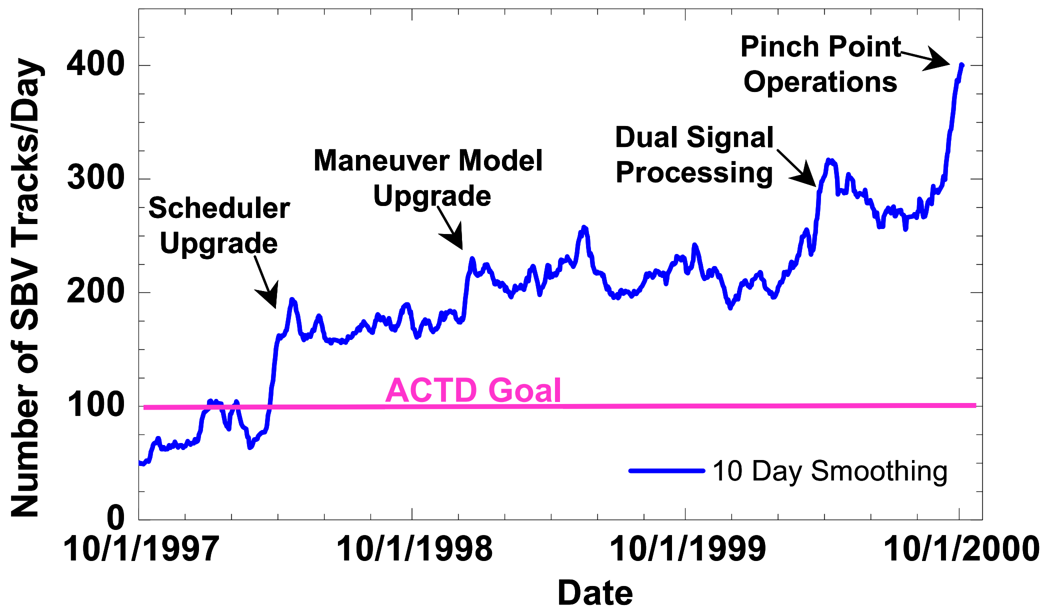


Figure 10. The increasing number of daily average deep space tracks collected by SBV have resulted from increasingly efficient use of spacecraft resources. Modifications of both ground and onboard software have increased the efficiency of scheduling and onboard signal processing.

This has increased beyond 350 tracks per day by October 2000. The productivity of SBV was increased through a combination of efficient data collection and efficient use of MSX spacecraft capabilities. The effective use of the SBV system is shown in Figure 6 which shows the percentage of time the SBV spends collecting data. This is the fraction of time the CCDs are collecting photons and producing framesets. The remaining fraction of the time is spent maneuvering the satellite and processing the data through the signal processor. A satellite maneuver is initiated immediately following the data collection, and signal processing is performed during the maneuver. The effectiveness of SBV has been increased by reducing the time the spacecraft spends maneuvering, and by reducing the effective processing time onboard the spacecraft. Initial efforts focused on reducing the amount time the MSX spacecraft spent maneuvering. Initially the maneuver durations were reduced from a constant 5 minutes to a constant 3-minute for all maneuvers independent of maneuver angle. The first increase in productivity resulted from reducing the maneuver duration and exploiting SBV's wide field of view to collect data on multiple objects simultaneously. This permitted the detection of more objects with the same number of maneuvers. Additional refinements in the maneuver model further increased the productivity by further reducing the maneuver duration. The next major increase in productivity was a result of the increased data processing capability onboard the spacecraft from the dual signal processing upgrade.

The final boost in productivity resulted from Pinch Point Operations, which combines the efficient use of the MSX spacecraft by searching a small region with small quick maneuvers and by placing the search region in dense regions of the GEO belt. The effect of the short maneuver time is apparent in Figure 11 that shows the increased fraction of time that is spent collecting data.

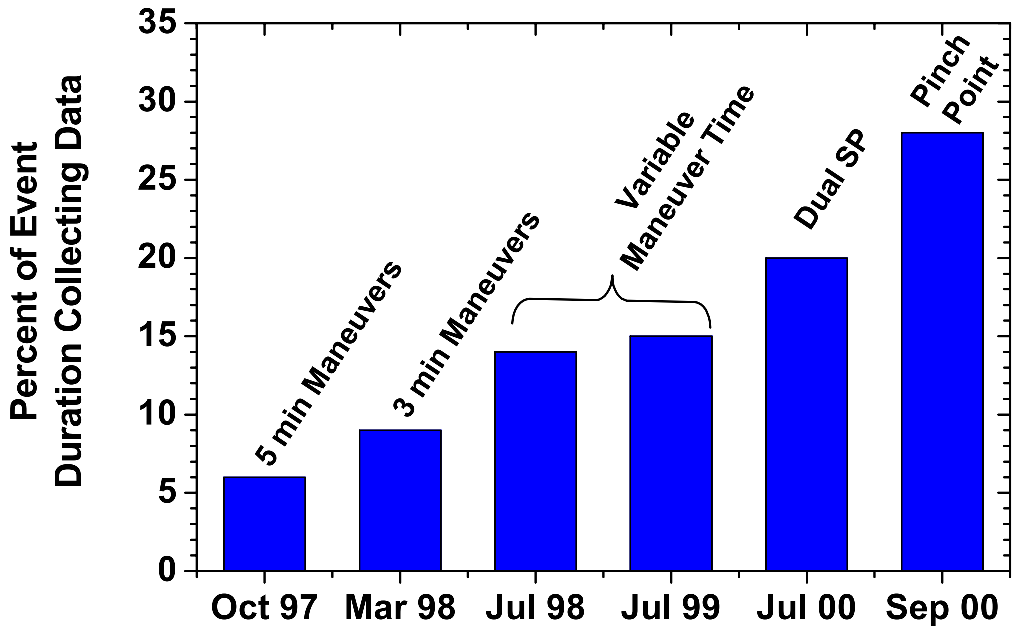
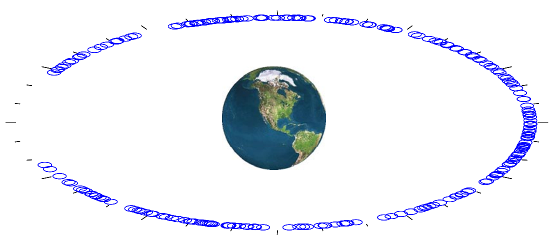
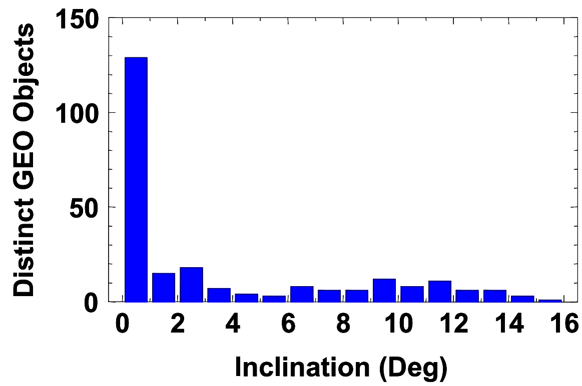


Figure 11. The fraction of time used for collecting data is a measure of how efficiently MSX/SBV system is used. The data collection time is the time required for collecting a frameset on a CCD. As the spacecraft maneuver time and signal processing time have been reduced, the amount of time devoted to data collection has increased from 5 to nearly 30 percent of the 8 hours per day that is used for space surveillance operations.

As illustrated earlier the pinch point coverage has resulted in increased productivity. The effectiveness of Pinch Point operations is illustrated in Figure 12, which shows the distribution in both longitude and inclination of all geosynchronous objects detected during Pinch Point Operations over a single day. Data from only search operations are shown in these results. Figure 12a shows the global coverage with only a gap over the Pacific Ocean as planned. Figure 12b shows that geosynchronous objects with both low and high inclinations are detected simultaneously at the pinch points.





Figures 12a-b An example of data collected over 24 hours illustrates the global coverage of Pinch Point operations and success of these operations in detecting high inclination GEO objects. The figure on the left shows the longitude distribution of detected GEO objects and the figure on the right shows the inclination distribution of these objects

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